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Letter

The beta-decay scheme of ^{232}Fr and the K = 0 ground-state band in ^{232}Ra

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Abstract. The beta-decay of ^{232}Fr to excited states in ^{232}Ra has been studied using gamma-gamma coincidence detection combined with the isotope separator on-line technique at the ISOLDE PSB facility at CERN. Earlier findings are confirmed and three new gamma lines are reported. In addition to the beta-decay characteristics of ^{232}Fr, the $K = 0$ ground-state band in ^{232}Ra is identified. A yield survey of neutron-rich Fr isotopes, important also for the EURISOL project, is incorporated.

PACS. 21.10.-k Properties of nuclei; nuclear energy levels – 23.20.-g Electromagnetic transitions – 28.60.+s Isotope separation and enrichment – 29.25.Rm Sources of radioactive nuclei

1 Introduction

Francium isotopes offer interesting possibilities to study atomic parity non-conservation which is closely related to lepton-quark interactions through Z^0 gauge boson exchange at small momentum transfer [1]. Thus they were selected by the NuPECC [2] as one of the key beams of future radioactive ion beam (RIB) facilities. One of these future RIB projects is called EURISOL [1]. To be able to make reliable performance predictions, data on release parameters [3] and yields of Fr isotopes from the ISOLDE PSB facility at CERN are needed [4]. In the present article some neutron-rich Fr yields and release parameters from the UC_x/graphite and ThC_x/graphite targets are reported. Due to the alkali element nature of Fr it can be efficiently extracted from the isotope separator on-line (ISOL) targets and ion source systems [5].

In addition to these yields, a more detailed beta-decay scheme for ^{232}Fr is presented. The isotope ^{232}Fr was discovered in Gatchina using the ISOL technique in 1990 [6]. Its half-life was measured to be 5(1) s. Despite its 5.7(7) MeV beta-decay Q-value [7] only one gamma-ray, at 125 keV, was reported. In 1998, the beta-decay of ^{232}Fr was briefly studied at ISOLDE. The outcome of that experiment was two new gamma-rays at 188.4(1) keV and 720.5(2) keV, an improved half-life 5.5(6) s, and the experimental decay scheme was developed for the first time [8]. In the present experiment we focused on confirming the earlier findings and on searching for transitions from the first-excited 2^+ state to the 0^+ ground state of ^{232}Ra.

2 Experimental method

All the Fr isotopes which were studied were produced by bombarding a 52 g/cm^2 thick UC_x/graphite target or a similar ThC_x/graphite target with 1.0 or 1.4 GeV protons from the PS booster (PSB) synchrotron at CERN. The PSB delivers protons in 2.0 μs long pulses with up to 3.2×10^{13} protons per pulse. The minimum time difference between the pulses is 1.2 s. After the irradiation, the reaction products have to diffuse out of the target material and then effuse into the surface ionization source. After ionization, the Fr isotopes are accelerated and mass separated. The use of a pulsed proton beam for isotope production provides a straightforward way to study the release behavior of different species from the different target and ion source units. In the yield and release measurements both the general-purpose separator (GPS) and the high-resolution separator (HRS) were used [4].

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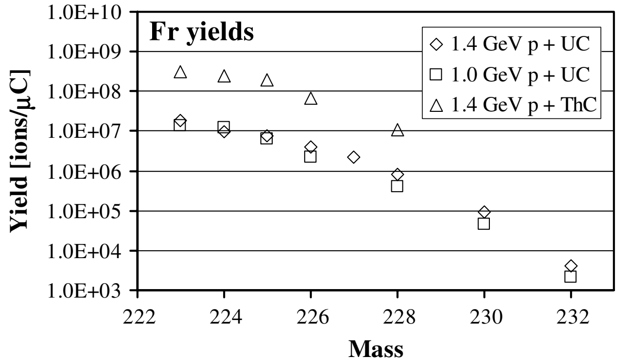

Fig. 1. Yields of neutron-rich Fr isotopes measured at the ISOLDE PSB facility at CERN.

The operational temperatures of the targets were about 2100 °C and the temperatures of the Nb surface ionizers were also about 2100 °C and the temperature of the W ionizer was about 2400 °C. The Fr yields were rather insensitive to the ionizer material, showing that the ionization efficiency is already close to 100% as expected from the low work function of Fr (4.07 eV). All yield and release data were measured using the monitoring tape station [3]. Isotope identification was based on half-life determination. Only in the case of the heaviest Fr isotopes, gamma-gamma data was also collected.

For ^{232}Fr, only a 35 min long spectroscopy measurement with 1.4 GeV protons was possible. In that experiment three proton pulses out of 14 in one super-cycle ($t_{\text{super-cycle}} = 1.2$ s $\times\, 14 = 16.8$ s) impinged on the HRS UC$_x$/graphite target. Pulses were spaced by 2.4 s each. Ten ms after each pulse, the beam gate was opened for 2380 ms. During that time, a mass-separated beam of ^{232}Fr was implanted in a movable tape viewed by a planar HPGe detector (3800 mm^2 in area and 20 mm thick) and a coaxial HPGe detector (70% relative efficiency). The tape was moved 10.5 s after the third pulse, thus leaving an undisturbed decay period of 8.11 s for gamma identification. The data were taken during the entire period.

The master trigger of the data acquisition system was a logical OR between the detectors. Gamma detector data were digitized and then stored using a VME-based data acquisition system. The energy and efficiency calibration of the detectors was based on ^{152}Eu, ^{147}Cs, ^{226}Fr and ^{230}Fr. A so-called isobaric contamination in the $A = 232$ spectra consisted of surface-ionized ^{232}Ra and ^{213}Ra^{19}F$^+$ molecules and their decay products. A second source of contamination came from nuclei studied earlier and from their decay products: ^{136}Cs, ^{230}Ra, ^{230}Ac and also from the beta-decay daughters of ^{232}Fr, including ^{232}Ra. All these contaminations were caused or influenced by the non-optimized ion beam optics. In addition to the tape, the mass-separated beam was also hitting the tape holder etc. and therefore could not be totally moved away from the detectors.

Table 1. Summary of gamma-decay transitions measured in this work.

E (keV)	Total intensity	$E2$ conversion coefficient
54.5(10)	160(70)	170(20)
124.7(10)	100(20)	3.9(4)
188.4(10)	32(7)	0.73(7)
670(2)	1.6(6)	
682(2)	3.2(8)	
721(2)	17(3)	

3 Results

Yields of the neutron-rich Fr isotopes from the UC$_x$/graphite and ThC$_x$/graphite targets are summarized in fig. 1. The UC$_x$/graphite target data show that the yields are about equal or slightly higher when using the 1.4 GeV proton beam compared to the 1.0 GeV proton beam. Figure 1 also shows that the ThC$_x$/graphite target is a better choice for the production of neutron-rich Fr isotopes. Clearly since ^{232}Th has only 142 neutrons, to go above ^{229}Fr the UC$_x$/graphite target is practically the only choice. The shape of the release curve can be reproduced reasonably well using eq. (1) [3,9]:

$$p(t) = \left(1 - \exp\left(-\frac{\ln 2t}{t_\mathrm{r}}\right)\right)\left(\alpha \exp\left(-\frac{\ln 2t}{t_\mathrm{f}}\right) + (1-\alpha)\exp\left(-\frac{\ln 2t}{t_\mathrm{s}}\right)\right). \quad (1)$$

The time constants in eq. (1) t_r, t_f and t_s govern the rise, the fast-fall and slow-fall times of the release function, respectively. The parameter α (between 0 and 1) determines the relative weight between the fast and the slow fall of the release curve. The fitted release parameters for the UC$_x$/graphite and ThC$_x$/graphite targets are: $t_\mathrm{r} = 120$ ms, $t_\mathrm{f} = 890$ ms, $t_\mathrm{s} = 8.3$ s, $\alpha = 0.85$ for UC$_x$/graphite and $t_\mathrm{r} = 35$ ms, $t_\mathrm{f} = 5.7$ s, $\alpha = 1$ for ThC$_x$/graphite.

From the $A = 232$ data three previously unknown and altogether six gamma-rays belonging to the beta-decay of ^{232}Fr were identified. A summary of these transitions is presented in table 1 with intensities corrected for internal conversion. Theoretical ($E2$) conversion coefficients used in the present work are also given in table 1. Conversion coefficients were derived by interpolating the data from [10]. Estimated uncertainties of interpolation are also given. The half-lives of the strongest transitions are in agreement with the earlier published half-life, 5.5(6) s [8]. In the case of the 54.5(10) keV transition, the statistics were too low for proper half-life determination. Nevertheless, the collected data are able to show that the 54.5(10) keV gamma is short-lived and therefore probably belongs to the beta-decay of ^{232}Fr. Figure 2 shows a low-energy portion of the single gamma-spectrum accumulated during the experiment.

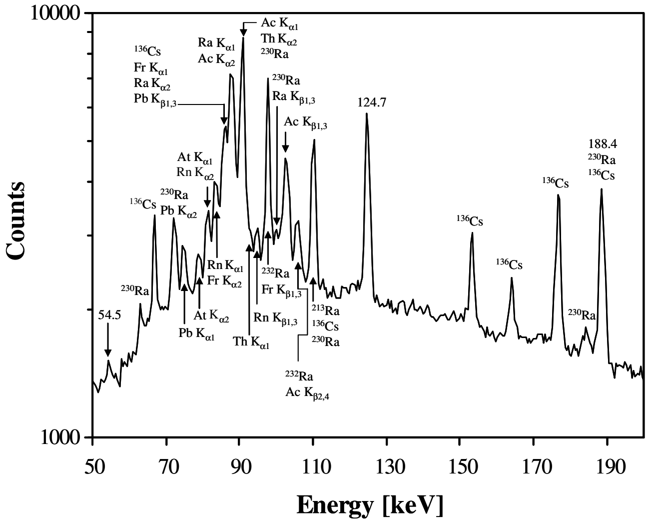

Fig. 2. Beta-delayed ^{232}Fr gamma-spectrum accumulated during the experiment.

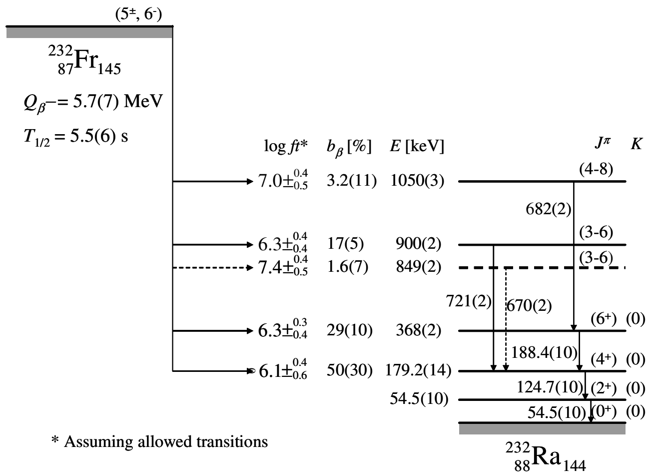

Fig. 3. A suggested beta-decay scheme for ^{232}Fr. Due to the low statistics, the transition marked with a dashed arrow should be treated with some caution.

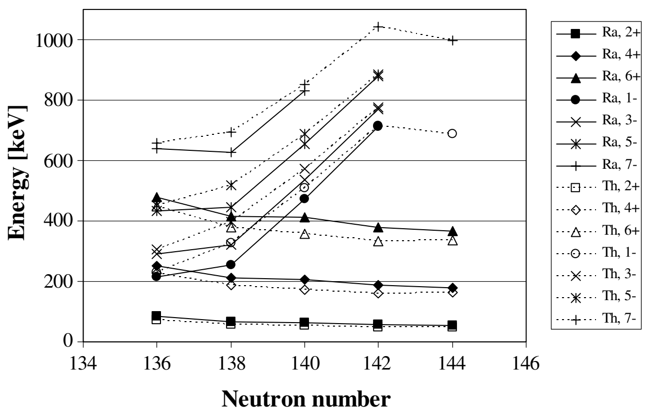

Fig. 4. Systematics of the first-excited states in $K^\pi = 0^+$ ($J = 2$, 4 and 6) and 0^- bands in even-even Ra and Th isotopes.

4 Analysis of the experimental data

The transitions shown in table 1 were placed in a decay scheme based on the gamma-gamma coincidence data and the energy/level systematics of even-even Ra/Th nuclei [11,12]. A suggested beta-decay scheme for ^{232}Fr is shown in fig. 3. Also shown are absolute beta-decay branching ratios b_β and $\log ft$ values assuming allowed beta-decay. The assumption of allowed beta-decay is made since all required spins and parities are not known. The measured $E(6^+ \to 4^+)/E(4^+ \to 2^+)$ ratio of 1.511(15) is close to that of an ideal rigid rotor, 1.57. This observation gives further confidence for the $K^\pi = 0^+$ ground-state rotational-band level assignments shown in fig. 3. Our statistics were too low to observe the 54.5(10) keV gamma in coincidence with the 124.7(10) keV transition. However, strong support for the placement of the 54.5(10) keV gamma as a 2^+-to-0^+ ground-state transition comes from the Ra and Th level systematics [11,12] as are shown in fig. 4. In addition, eq. (2) [13] together with the experimental energies of the proposed 6^+ and 4^+ states suggests that the first-excited 2^+ state in the ground-state rotational band of ^{232}Ra would lie at 54.5 keV. Equation (2) predicts the energy of a rotational state and it results from a calculation in which the coupling of intrinsic and rotational motions is taken into account:

$$E = \frac{\hbar^2}{2J} I(I+1) + LI^2(I+1)^2 + MI^3(I+1)^3 . \qquad (2)$$

In eq. (2), J is the moment of inertia, I is the angular-momentum quantum number and L (magnitude about $10^{-3}\hbar^2/2J$) and M (magnitude about $10^{-5}\hbar^2/2J$–$10^{-6}\hbar^2/2J$) are small correction terms. In the above calculation, M was set to zero, L became -9.3×10^{-6} MeV and J became 54.7 $\hbar^2$/MeV.

For states of ^{232}Ra to be significantly populated in the beta-decay of ^{232}Fr, beta-feeding to those states would have to be of allowed or first-forbidden strength. Since we observe strong beta-feeding to both the 4^+ and 6^+ states, the possible ground-state spin of ^{232}Fr is restricted to 5^+ (only allowed beta-decay possibility) and 4^-, 5^- and 6^- (first-forbidden possibilities). These spins exclude direct ^{232}Fr ground-state to ^{232}Ra ground-state beta-decay. The Ra and Th level systematics [11,12] suggest that the 3^- and 5^- states belonging to a $K^\pi = 0^-$ band should appear between 0.6 and 1 MeV in ^{232}Ra (see fig. 4). If the ground-state spin of ^{232}Fr were 4^-, then we should observe allowed beta-decay into both of those states. The non-observation of such a feeding pattern leads us to conclude that the ground-state spin cannot be 4^-. This conclusion then rules out significant beta-feeding directly into the first 2^+ state in ^{232}Ra. Within the respective experimental uncertainties this is consistent with the data listed in table 1 by assuming an $E2$ transition. The proposed spin ranges of the higher excited states in ^{232}Ra shown in fig. 3 are based on the ^{232}Fr ground-state spin choices discussed above and on the gamma-decay characteristics of those states. The evolution of the ground-state $K^\pi = 0^+$ band and the $K^\pi = 0^-$ band as a function of neutron number is summarized in fig. 4.

5 Conclusions

The results of this work confirm the smooth continuation of the ground-state rotational-band systematics within even-even Ra isotopes while moving further out to ^{232}Ra. Due to the high Z and the low energy of the 2^+-to-0^+ transition, its 54.5(10) keV gamma is highly converted and therefore difficult to detect with the HPGe detectors. Data presented now identify this 2^+-to-0^+ transition for the first time but with low statistics. These statistics would be easy to increase by at least a factor of 100 just by extending the collection time from 35 min to few days. Such a longer measurement would also dramatically improve the accuracy of the rest of the decay scheme. In addition to the standard gamma-gamma data collection, a short run using a conversion electron spectrometer would also be useful. Based on the present neutron-rich Fr yields at CERN/ISOLDE, shown in fig. 1, the detection of ^{233}Fr should also be possible. We would also like to note that, given the yields presented here for Fr isotopes, EURISOL should be able to fulfill the Fr beam intensity expectations set for it.

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